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### *Ice growth on Post Pond, 1973 - 1982*

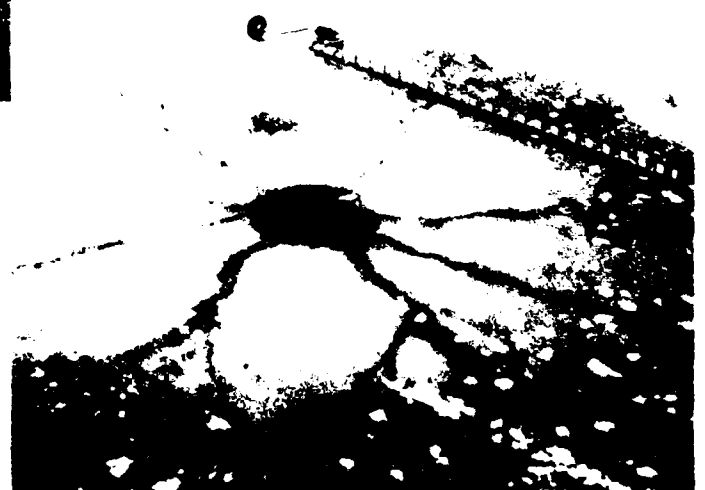


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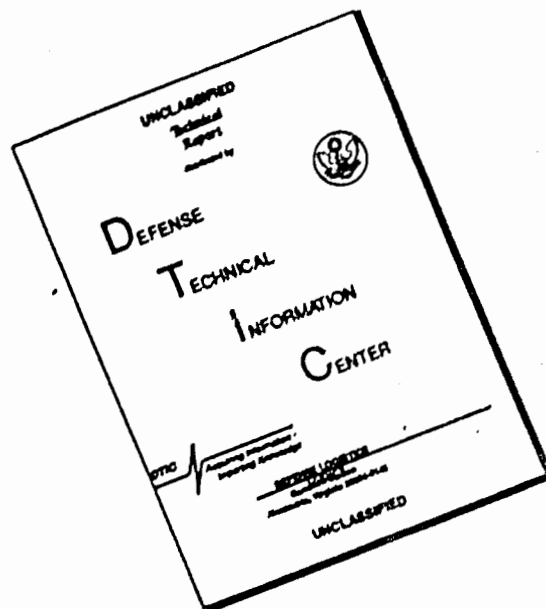
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# CRREL Report 83-4

February 1983

## *Ice growth on Post Pond, 1973 – 1982*

Anthony J. Gow and John W. Govoni

Prepared for

OFFICE OF THE CHIEF OF ENGINEERS

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20. Abstract (cont'd).

lake water, but snow ice may compose as much as 50% of the ice cover in winters with higher than average snowfall. Freeze-up leading to the establishment of a stable ice cover occurs during the 4-week period from the end of November to the end of December. Maximum seasonal ice thicknesses were from 45 to 67 cm and are generally attained during the first two weeks of March; ice-out, marking the final disappearance of ice from Post Pond, usually occurs by the third week of April. The overall rate of ice loss is three to four times that of ice growth, and is dominated initially by melting from the top. As much as 50% of the ice may be lost in this way before the onset of any bottom melting. Final dissipation of the ice cover is usually expedited by candling resulting from preferential melting and disintegration of the ice at crystal boundaries.

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# **PREFACE**

This report was prepared by Dr. Anthony J. Gow, Geologist, and John W. Govoni, Physical Science Technician, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. This report is published under DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground, Task A, Work Unit 001, Physical Properties of Snow and Ice.*

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# ICE GROWTH ON POST POND, 1973-1982

Anthony J. Gow and John W. Govoni

## INTRODUCTION

The purpose of this report is to summarize several years' measurements of the growth and dissipation of ice covers on Post Pond in Lyme, New Hampshire. These measurements were performed in conjunction with the authors' studies of the physical, structural and mechanical properties of temperate lake ice, centered on investigations at Post Pond. This work was directed towards understanding the bearing capacity and trafficability characteristics of lake ice sheets. These properties depend to a large degree on the structural makeup of the ice, which reflects the condition under which the ice sheet grows, matures and decays. Results of observations obtained since our studies were initiated in the winter of 1973-74 are contained in a series of reports mainly devoted to the mechanical and physical properties of Post Pond ice (Gow and Langston 1975, Gow 1977, Gow and Langston 1977, Gow et al. 1978, Gow, in press).

Beginning with the winter of 1973-74 the growth and decay of ice on Post Pond has been monitored each year to the present. Observations have included ice thickness measurements, identification of the various ice types contributing to the ice cover, and measurements of meteorological parameters for correlating with and modeling ice growth. The major objectives of the work described in this particular report were 1) to determine the variability in the timing and duration of freeze-up and dissipation of the ice cover on Post Pond, 2) to

ascertain the nature of the ice growth and decay process on the pond, 3) to evaluate year-to-year variations in winter air temperatures at Post Pond, and 4) to examine the relationship of ice growth to freezing degree-days ( $^{\circ}\text{C}$ ) measured at Post Pond and at CRREL.

## LOCATION OF STUDY

In 1968 Parrott and Fleming (1970) established a CRREL test facility on Post Pond for investigating the year-round thermal structure of Post Pond; this facility has continued to be used for a variety of ice-related projects. Post Pond (Fig. 1) is a small eutrophic lake of glacial origin situated approximately 3 km north of the town of Lyme, New Hampshire, and about 20 km from CRREL. The pond is in a region of cool temperate climate with a mean annual temperature of  $+7^{\circ}\text{C}$  and with minimum temperatures as low as  $-35^{\circ}\text{C}$ . It covers approximately  $0.46\text{ km}^2$ , has a maximum depth of about 12 m, and is thermally dimictic, i.e. it generally circulates twice a year. Trout Brook, the major stream entering Post Pond, is located less than 300 m from Clay Brook, the major outlet stream, which ultimately flows into the Connecticut River several kilometers northwest of Post Pond. Details of the origin, physiographic setting, hydrology and thermal characteristics of Post Pond were given by Ragle (1963) and Parrott and Fleming (1970).





Figure 1. Air photo of Post Pond, showing locations of the primary ice-thickness measurement sites.



Figure 2. Vertical section through an ice cover as seen in the side view of a large beam cut from the ice. The section shows snow ice (S) overlying lake ice containing several distinctive layers of entrapped air bubbles. In this instance the amounts of snow ice and lake ice are about equal.

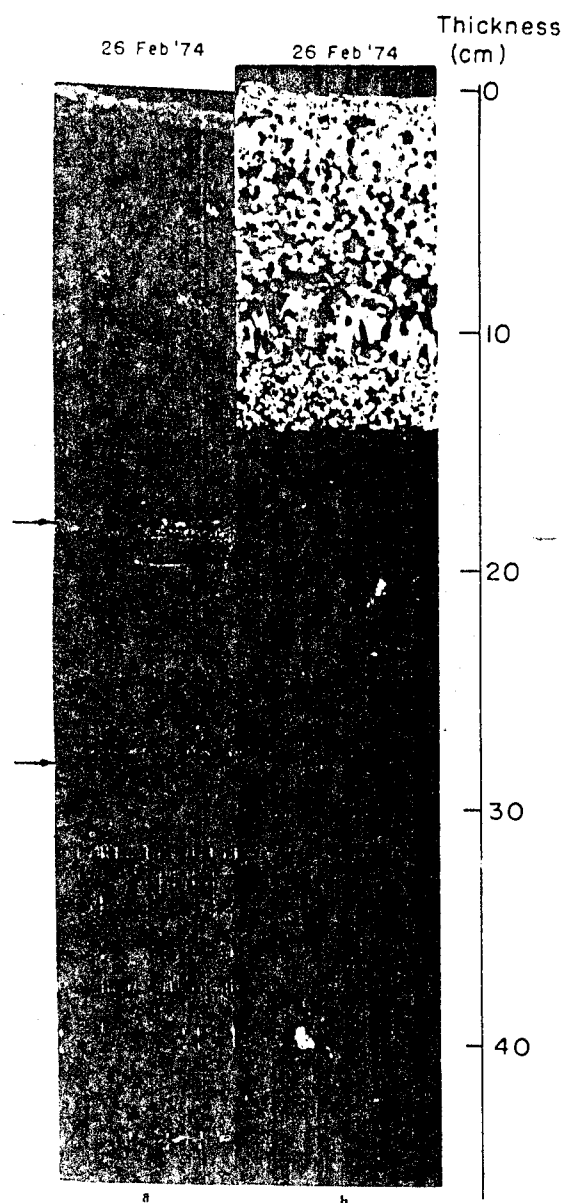


Figure 3. Vertical thin sections of ice from Post Pond showing stratigraphic (a) and structural (b) characteristics. The layering in a is the result of air bubbles in the ice. In b, photographed between crossed polaroids to reveal the crystalline texture of the ice, the transition between snow ice (on top) and lake ice is especially well marked. The lake ice is composed entirely of large, prismatic crystals with vertical c-axes. In this section several episodes of snow-ice formation can be distinguished on the basis of grain-size differences.

## STUDY METHODS

### Ice thickness

Each season, ice thickness measurements were initiated at the edge of Post Pond and continued until the ice was thick enough to establish sampling sites farther out on the lake. In 1973-74 these measurements were made at a large number of locations, mainly to determine variations in ice thickness with location on the lake. There were no significant variations in ice thicknesses measured at sites located 25 m or more from the shore (Gow and Langston 1977) (Fig. A1). Accordingly all subsequent measurements of ice thickness were obtained by averaging measurements made weekly at three or four locations along a line beginning about 25 m offshore and extending just beyond the center of the lake (Fig. 1). The majority of ice thickness measurements were obtained from holes drilled through the ice sheet. These data were supplemented with measurements made in connection with in situ testing of large ice beams (Gow and Langston 1975, Gow et al. 1978) and on blocks of ice used for investigating the crystalline structure of the ice sheet at different stages of its growth.

### Ice-cover composition

Post Pond ice covers are typically composed of two kinds of ice: lake ice and snow ice. Lake ice is formed as lake water freezes to the underside of the ice cover. Snow ice is formed on top of the ice sheet as water-soaked snow freezes. (Sometimes the terms "white ice" and "black ice" are used for snow ice and lake ice, respectively, but the latter terms are preferred here because of their genetic significance.) The two types of ice are readily distinguished visually in the walls of a hole drilled into the ice cover or on a block cut from the ice sheet. The differences observed in an ice beam (Fig. 2) are demonstrated even more vividly in a vertical thin ( $< 0.5$  mm) section of the ice sheet placed between crossed polaroids (Fig. 3). The small equant crystals and abundant air bubbles in the snow ice are easy to distinguish from the coarse-grained, vertically elongated crystals of the underlying lake ice. Snow ice always forms by the infiltration and freezing of water in snow. Mechanisms by which water infiltrates snow on Post Pond include uprise of lake water through cracks in the ice, downward percolation of rainwater, snowmelt, and discharge of flood water onto the snow-covered lake ice from streams along the shore, particularly Trout Brook. Since water-soaked snow usually freezes from the top down, it is not uncommon to find layers of unfrozen water

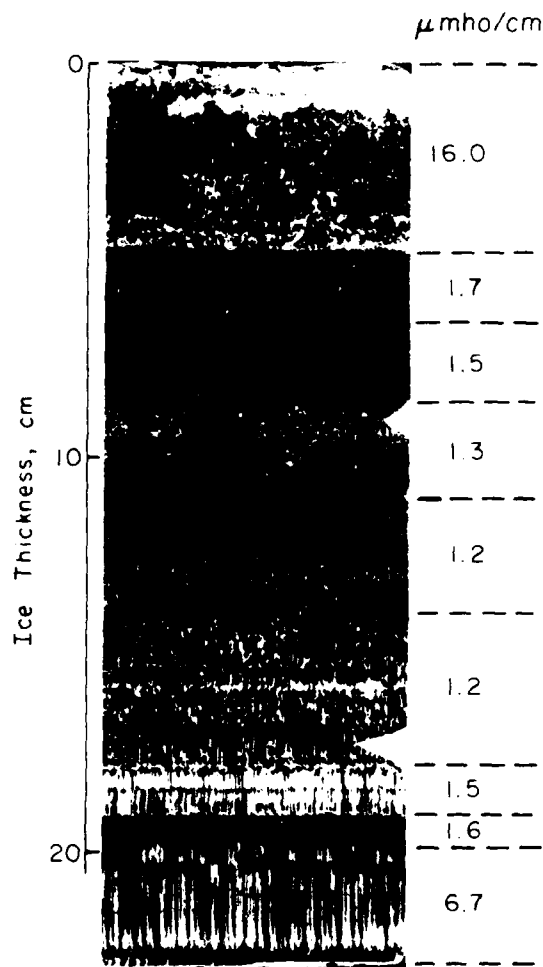


Figure 4. Ionic (electrolytic) conductivity profile obtained on meltwater samples from the Post Pond ice cover, 18 January 1974.

sandwiched between lake ice and snow ice. These mechanisms and their impacts on snow ice formation on Post Pond were discussed in more detail by Gow and Langston (1977). A detailed discussion of the structural characteristics of the lake ice is beyond the scope of this report. Suffice it to say that the crystalline structure of Post Pond lake ice has remained remarkably constant from winter to winter. As indicated in Figure 3 this structure is dominated by the growth of large, vertically elongated crystals with vertical c-axis orientations (Gow 1975).

As demonstrated by Gow and Langston (1977) the natural freezing of lakes usually leads to significant partitioning of the chemical constituents in the water. Figure 4 demonstrates the extent to

which soluble ions are rejected by the freezing of water with an original ionic conductivity of 60-80  $\mu\text{mho}/\text{cm}$ . Only the snow ice shows an elevated conductivity. In this instance the lake itself was the source of infiltrating water, and it constituted about 20% by volume of the snow ice.

#### Surface air temperatures

During October 1974 a standard instrument shelter was erected on the edge of Post Pond. This shelter was equipped with a seven-day, clock-driven, mechanical hygrothermograph for measuring air temperatures continuously throughout the winter and maximum and minimum thermometers for calibration. Excellent records were obtained during the winters of 1974-75 and 1975-76. Unfortunately these measurements had to be terminated during the 1976-77 winter because of repeated vandalism. However, a comparison of records obtained at Post Pond with those routinely measured at CRREL, 20 km south, revealed no significant differences in average daily temperatures between the two sites. (An earlier analysis by Gow and Langston [1977], based mainly on air temperature records from the Dartmouth College Weather Observatory in Hanover, New Hampshire, had indicated that winter daily temperatures at CRREL might average as much as 0.5 °C warmer than those measured on Post Pond, but more recent measurements indicate that this is not the case.) Accordingly we have depended on temperatures measured at CRREL to calculate freezing-degree-day data for analyzing ice sheet growth on Post Pond.

Of primary interest here are the daily maximum and minimum air temperatures, which are used for calculating the freezing-degree-day number  $S_d$ . This number, a very useful index of winter temperature regime, is usually obtained from

$$S_d = 0^\circ\text{C} - \frac{T_{\max} - T_{\min}}{2} \quad (1)$$

where  $T_{\max}$  and  $T_{\min}$  are the daily maximum and minimum air temperatures, respectively.

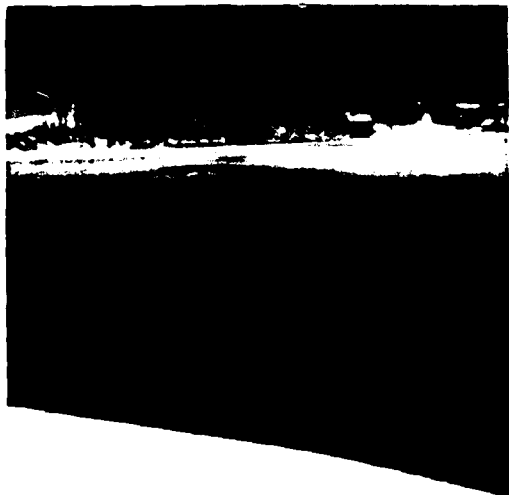
Day-by-day summations of  $S_d$  yield cumulative freezing-degree-day (°C) records that have proved useful in demonstrating year-to-year variations in winter temperature regimes. In addition the concept of freezing-degree-days has been used widely in conjunction with the simple Stefan heat conduction equation to estimate and/or predict ice growth on rivers and lakes (for example, Bilello 1964, Michel 1971, Ashton 1974, 1978 and Bates 1980). Both of these applications of freezing-

degree-day records are used in this report to evaluate air temperature regimes and ice growth on Post Pond for the period 1973-1982.

### FREEZE-UP AND ICE-OUT CHARACTERISTICS

Freeze-up, here defined as corresponding with the date that a permanent winter ice cover be-

comes established, is usually preceded by one or more episodes of freeze-over. Freeze-over occurs whenever the surface of a lake or a substantial part of it skims over with ice. Occasionally initial freeze-over may coincide with freeze-up if air temperatures across the surface of the pond remain low enough to allow a stable ice sheet to form (4-6 cm thick). Any rapid onset of freeze-up is usually preceded by lower-than-normal air temperatures, which lower temperatures in the near-surface



*a. Ice cover partially established, 19 December 1974.*



*b. Ice cover fully established, 26 December 1974.*



*c. Midwinter ice cover, late February 1975.*



*d. Shoreline moat and fragmenting ice cover signaling approach of ice-out, mid-April 1975.*

*Figure 5. Stages of growth and decay of the ice cover on Post Pond during the winter of 1974-75.*



*Figure 6. Ice-growth boundary of the kind shown in Figure 5b. The ice on either side of the boundary formed approximately four days apart.*

water column sufficiently close to  $0^{\circ}\text{C}$  to encourage early formation of a stable ice sheet by direct freezing of the lake water. Such a sheet usually grows several centimeters thick before any significant accumulation of snow occurs. The effect of snow is twofold: while it impedes lake ice growth by virtue of its insulating properties, it can, when infiltrated by water, supplement ice sheet thickening by forming snow ice. Occasionally, however, the onset of freezing is accompanied by snowfall sufficiently thick to create slush on top of the water, which, if conditions remain cold enough, can freeze to form a stable ice cover. A more general situation on Post Pond is a progressive freeze-up in which separate areas of the pond freeze over independently before they finally coalesce to form a shore-to-shore ice cover. Depending on the weather pattern in any particular year, as much as a month may elapse between the initial appearance of ice on Post Pond and final freeze-up. Following freeze-up the ice sheet continues to grow downward by freezing of the lake water (a process sometimes referred to as congelation) and upward by the formation of snow ice.

Dissipation of the ice cover on Post Pond usually begins during the latter part of March and is usually complete by the third week of April. This process is dominated initially by surface melting until the ice sheet becomes thin enough ( $< 20\text{ cm}$ ) and so weakened by candling (gross mechanical weakening of the ice cover by preferential melting

along the grain boundaries of the component crystals) that even light winds can cause it to disintegrate. Occasionally Post Pond will clear itself of ice by wind rafting and pile-up of ice sheet fragments along the shore. The final disappearance of ice from the pond is defined as ice-out. Ice-out and freeze-up characteristics vary from year to year and are treated in greater detail in subsequent sections of this report.

The sequence for the winter of 1974-75 (Fig. 5) is fairly typical of the ice growth and decay on Post Pond. A close-up view of the boundary separating ice that formed several days apart (as shown in Figures 5a and b) is given in Figure 6. On 26 December some unusual circular structures, up to 2 m in diameter, that had formed in ice less than 5 cm thick were observed (see cover). These structures were all located within 200 m of the shore along the northern edge of the pond. In a number of cases the top of the ice extending for some distance beyond the edges of the structures was distinctively ripple-marked. Though the structures were not observed as they formed, the occurrence of the ripples, together with observations made on vertical sections of several of the structures themselves indicate that they originated as melt holes resulting from the upwelling and overflow of warm water, possibly from springs on the bottom of the pond. The subsequent refreezing of water in the melt holes probably exerted sufficient pressure on the thin ice at the edges of the holes to create

the radiate crack patterns. Similar structures were occasionally observed in subsequent winters, but never in ice thicker than 5 cm and never in the profusion that was observed on 26 December 1974.

## RESULTS AND DISCUSSION

### Ice-growth records

Ice-growth histories, regional surface air temperatures, and summary accounts of each year's ice growth and dissipation are presented in Appendix A. The overall shapes of the growth and decay curves show some variation, mainly in the lag between the attainment of maximum ice thickness and the onset of melting. The average ice-growth velocities varied from 5 mm/day (1979-80) to 9 mm/day (1980-81). By contrast the average ice dissipation rates varied from 17.5 mm/day (1975-76) to 23 mm/day (1977-78). These data and the records in Appendix A show that once ice loss begins, it occurs three to four times as fast as ice growth. The ice cover usually dissipates without a break until the ice cover has completely disappeared. Occasionally a period of substantial melting may be interrupted by resumption of ice growth followed by renewal of ablation (e.g. 1978-79 and 1980-81). The premature thaw beginning the second week of February 1981 is especially well documented since it resulted in thinning of the ice from 59 to 30 cm in about 10 days (Fig. A8). In 1979-80 the ice grew fairly uniformly (5 mm/day) until it reached its maximum thickness, which was followed almost immediately by virtually uniform thinning of the ice at a rate four times that of ice growth (20 mm/day). A case of "leveled out" growth is exemplified by the winter of 1977-78. Beginning with freeze-up the ice grew at a nearly uniform rate of 8.6 mm/day until it was 62 cm thick (about 10 weeks later); it did not reach its maximum thickness (67 cm), however, until nearly five weeks later. This was followed by rapid melting at a rate that averaged 23 mm/day.

Lake ice was the predominant ice type on Post Pond for the period 1973-1982. The contribution of snow ice to the total ice thickness varied from 50% in 1975-76 to less than 7% in 1980-81. The total ice thickness varied from 45 cm in 1973-74 to 67 cm in 1977-78 and 1981-82.

The major ice events for 1973-1982 are listed in Table 1, which shows that freeze-up can occur as early as the end of November or as late as the fourth week of December. Dates of maximum ice thickness are highly variable, ranging from 9 February to 24 March. Ice-free dates were all in April,

Table 1. Post Pond ice-cover data.

Winter	Freeze-up date	Max. ice thickness (cm)	Max. ice date	Ice-free date
1973-74	17 Dec	45	24 Feb	19 Apr
1974-75	26 Dec	47	10 Mar	20 Apr
1975-76	17 Dec	60	16 Mar	20 Apr
1976-77	29 Nov	52*	15 Feb	N.D.
1977-78	10 Dec	67	24 Mar	29 Apr
1978-79	13 Dec	58	24 Feb	13 Apr
1979-80	18 Dec	54	12 Mar	11 Apr
1980-81	6 Dec	59	9 Feb	7 Apr
1981-82	14 Dec	67	15 Mar	27 Apr

\* Thickness data unreliable because of activities of ice fishermen, leading to widespread depression and flooding of the ice cover.

Table 2. Duration of ice cover on Post Pond.

Winter	Time from freeze-up to max. thickness (days)	Time from max. thickness to ice-out (days)	Duration of ice cover (days)
1956-57*	82	57	139
1968-69†	88	42	130
1973-74	70	54	124
1974-75	75	41	116
1975-76	91	35	126
1976-77**	—	—	—
1977-78	105	36	141
1978-79	74	48	122
1979-80	86	30	116
1980-81	65	57	122
1981-82	92	43	135

\* Data from Ragle (1963).

† Data from Parrott and Fleming (1970).

\*\* No reliable data available.

with the earliest on 7 April and the latest on 29 April. There appears to be no systematic relationship between these events, at least not of a predictive nature, implying that these events are controlled solely by weather.

Table 2 shows the time to maximum ice thickness and the ice cover duration for each winter from 1973 to 1982. The time from freeze-up to maximum ice thickness varied from 70 days to 105 days. The duration of the ice cover ranged from 116 to 141 days, and the time between the ice maximum and ice-out varied from 30 to 57 days.

Trapped air bubbles are characteristic of ice formed from lake water; layers of bubbles can be seen in the stratigraphic section in Figure 3. In this instance very rapid freezing between 22 and 25 December 1973 led to the formation of a distinctive

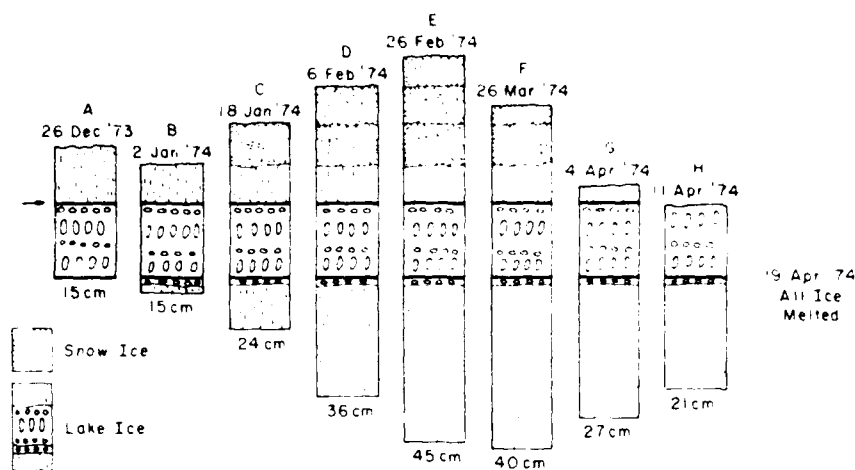


Figure 7. Stratigraphic sections illustrating sequential growth and decay of the Post Pond ice cover (1973-74). All sections are referenced to the top of a diagnostic bubble zone marked by an arrow beside section A.

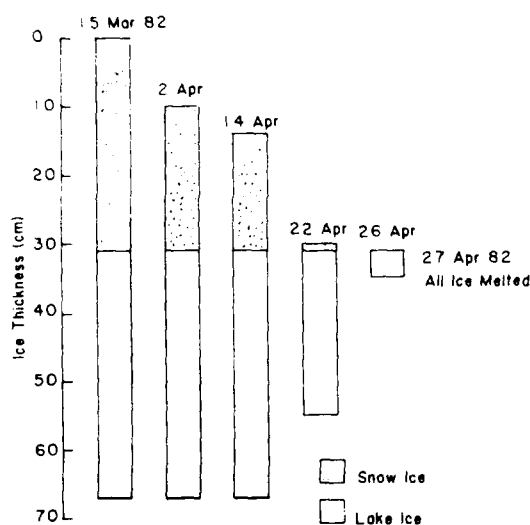


Figure 8. Stratigraphic sections demonstrating the nature of ice loss on Post Pond (1982). All sections are referenced to the bottom of a very thick snow-ice layer.

bubble zone (between the arrows in Figure 3). Because this bubble zone could be traced across the entire lake, it was used as a reference layer for monitoring all subsequent growth and decay of the ice cover, both from above and below.

Ice blocks excavated during the 1973-74 winter allowed the major ice events to be reconstructed (Fig. 7). Between sections A and B was a warm period at the end of December, and 2 cm of ice was lost from the top. This loss was subsequently

balanced by the growth of 2 cm of ice on the bottom. Section C reflects both an addition of snow ice on the top and continued growth of ice on the bottom. The snow ice formed from the freezing of water that had infiltrated snow that fell between 9 and 11 January. With further periodic accretion of snow ice and continued freezing of lake water at the bottom, the ice cover continued to thicken, as indicated in sections D and E. Section E represents the Post Pond ice sheet at its thickest, when it was composed of 13 cm of ice and 32 cm of lake ice. By 26 March the ice sheet had thinned from 45 cm to 40 cm, entirely as the result of snow ice melting from the upper surface. An additional 13 cm of ice was lost by 4 April (section G), including all the snow ice. Only 21 cm of ice remained by 11 April, by which time the ice had begun to candle. Mechanical degradation of ice by candling, leading to increased permeability to water, is a major factor in the final disintegration of Post Pond ice covers.

Ice is lost both from the top and bottom by melting (Figs. 7 and 8). Melting from the top predominates as the ice sheet begins to melt on Post Pond, particularly for ice covers with thick snow ice. In some years melting from the top surface accounted for as much as 70% of the total ice loss immediately preceding candling and final disintegration of the ice sheet. These observations for Post Pond are in general agreement with those of Williams (1966) for Canadian lakes.

For comparison with Post Pond, ice thicknesses were measured on several other lakes in New Hampshire and Vermont, all within 30 km of Post

**Table 3. Maximum ice thickness (cm) for selected lakes in New Hampshire and Vermont (1973-1982).**

Winter	Post Pond (Lynde, N.H.)	Muscoma Lake (Enfield, N.H.)	Canaan Street Lake (Canaan, N.H.)	Crystal Lake (Enfield, N.H.)	Lake Morey (Fairlee, Vt.)	Lake Fairlee (Fairlee, Vt.)
1973-74						
Snow ice	13	13	—	—	—	—
Lake ice	32	38	—	—	—	—
Total	45	51	—	—	—	—
1974-75						
Snow ice	09	30	24	24	06	20
Lake ice	38	34	25	23	36	29
Total	47	64	49	47	42	49
1975-76						
Snow ice	30	20	24	22	21	36
Lake ice	30	41	29	26	30	25
Total	60	61	53	48	51	61
1976-77						
Snow ice	—	—	18	24	07	14
Lake ice	—	—	37	32	37	33
Total	—	—	55	56	44	47
1977-78						
Snow ice	17	26	32	25	18	25
Lake ice	50	52	41	45	49	41
Total	67	78	73	70	67	66
1978-79						
Snow ice	23	24	23	27	21	24
Lake ice	35	35	34	29	33	22
Total	58	59	57	56	54	46
1979-80						
Snow ice	5	9	6	8	9	12
Lake ice	49	50	45	51	48	49
Total	54	59	51	59	57	61
1980-81*						
Snow ice	4	10	2	7	5	9
Lake ice	55	32	46	42	47	35
Total	59	42	48	49	52	44
1981-82						
Snow ice	31	44	54	38	32	39
Lake ice	36	20	20	31	29	23
Total	67	64	74	69	61	62

\* Except for Post Pond all the ice thickness data were obtained during the latter part of January 1981 before these lakes had reached maximum thickness. An unusually early and severe thaw during February 1981 prevented measurements of maximum ice thickness on these lakes.

Pond (Table 3). Because of differences in topography and exposure, some lakes accumulate less snow, and hence less snow ice, than others. Post Pond, for example, usually incorporates less snow ice than any of the other lakes. Generally, in all the lakes studied, there was more lake ice than snow ice, but appreciable variations in the ratio of the two ice components can occur from year to year, mainly due to the regional pattern of snowfall. The winters of 1979-80 and 1980-81 both had exceptionally low snowfalls in New Hampshire and Vermont; only small amounts of snow ice formed, less than 20% on all six lakes. By contrast, in 1982-82 exceptional amounts of snow ice were produced; at all the lakes except Post Pond, the snow ice was thicker than the lake ice by ap-

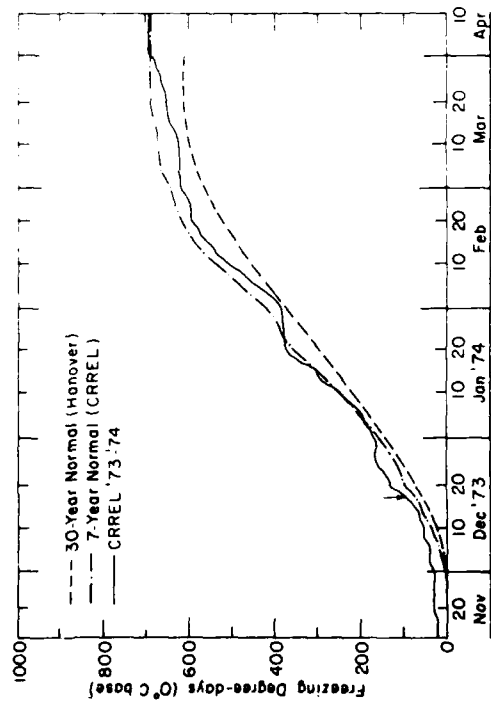
preciable amounts, in some cases by more than 2:1.

#### Freezing-degree-day records

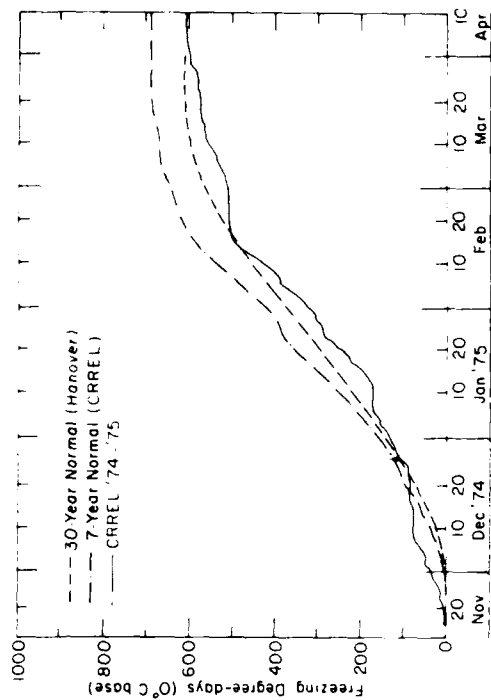
Cumulative freezing-degree-day records (0°C base) for CRREL for 1973-1982 are presented in Figure 9. Records obtained at Post Pond for the winters of 1974-75 and 1975-76 are presented in Figure 10. Included for comparison are the 7-year-normal curve for CRREL for the winters of 1973-74 through 1979-80,\* and the 30-year-normal

\* Though the thickness data presented here include the winters of 1980-81 and 1981-82, plots of the first 7 years were prepared and the manuscript of this report substantially drafted before the data from 1980-81 and 1981-82 were reduced.

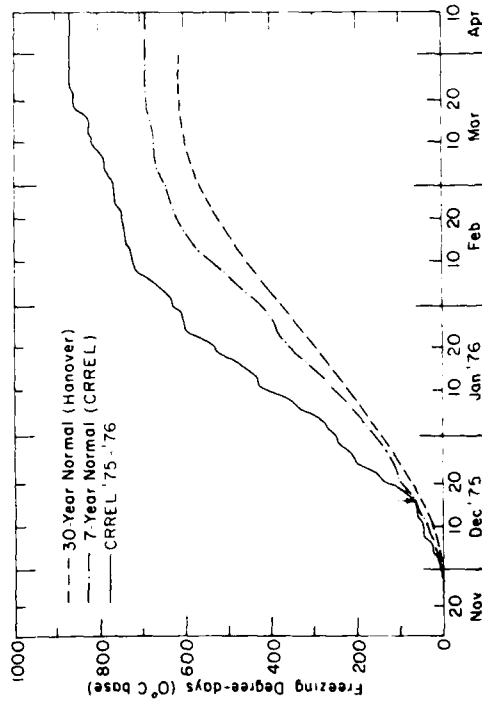




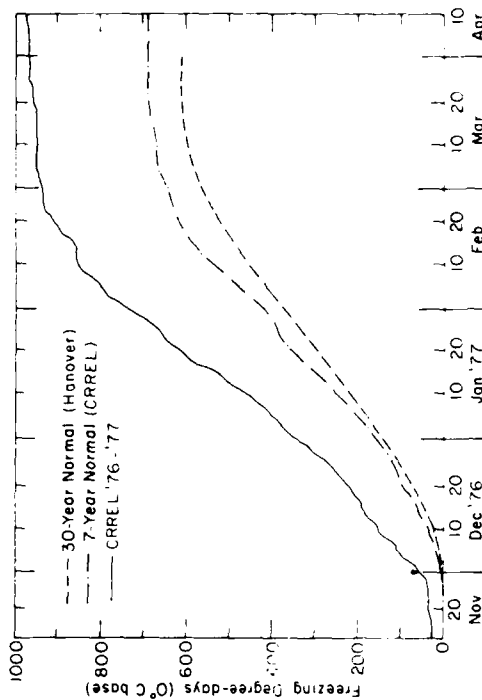
a. 1973-74.



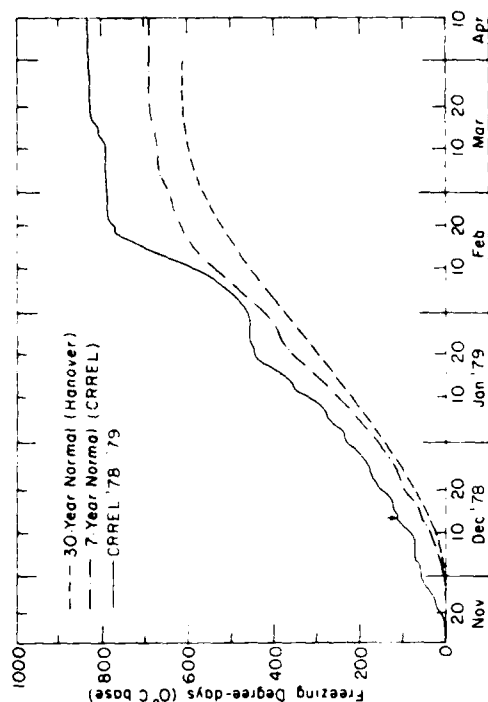
b. 1974-75.



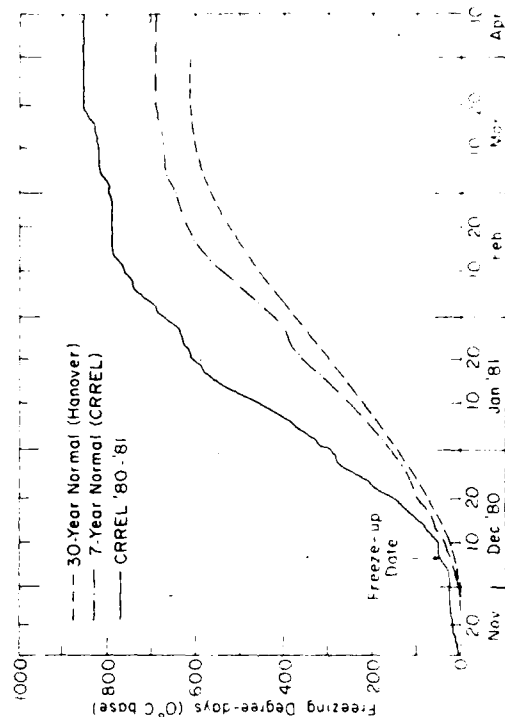
c. 1975-76.



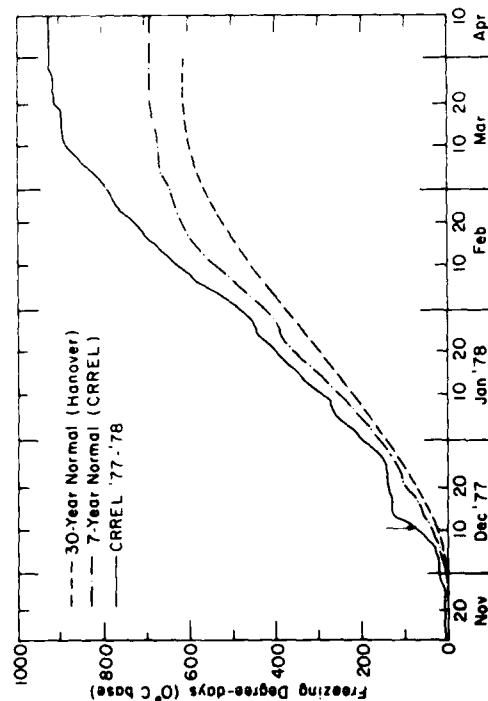
d. 1976-77.



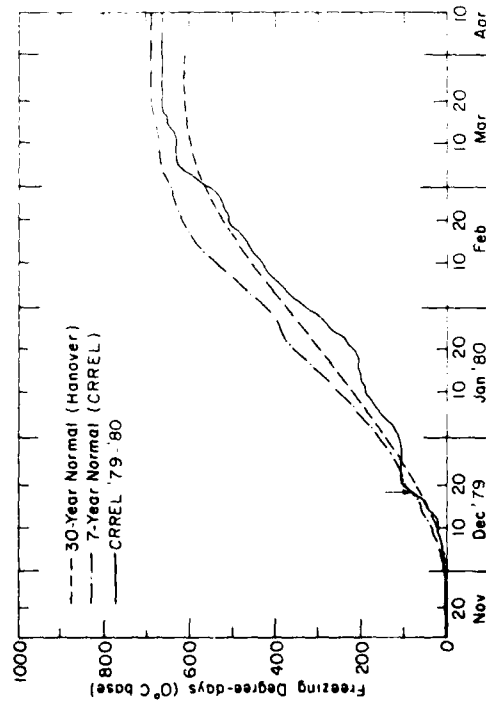
f. 1978-79.



h. 1980-81.



e. 1977-78.



g. 1979-80.

Figure 9. Cumulative freezing-degree-day records for CRREL for 1973-1982. The curves are based on the Hanover Cooperative Station's 30-year normal (1941-1970) and the CRREL meteorological station's 7-year average (1973-1980). Freeze up dates are indicated by arrows.

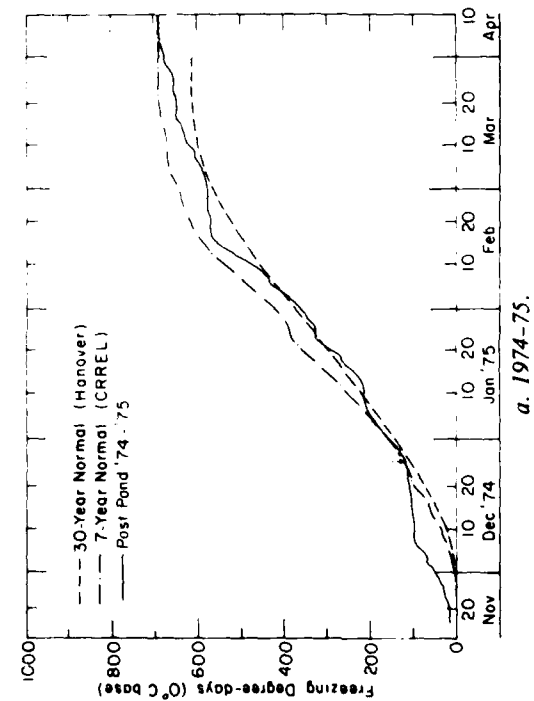
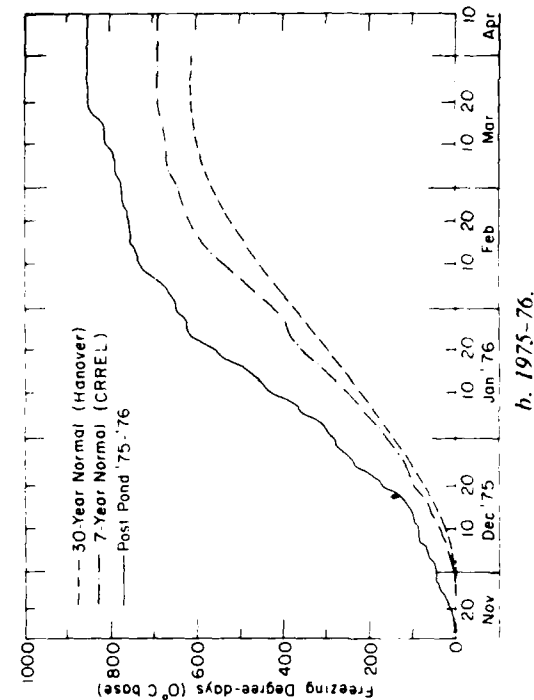
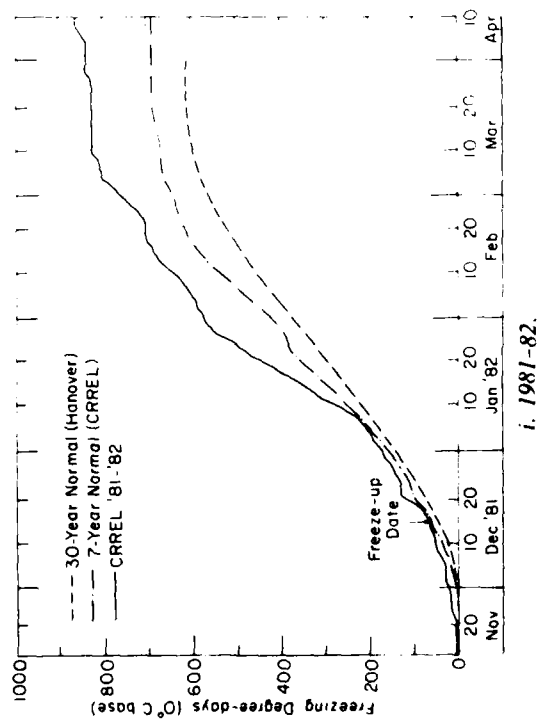


Figure 9 (cont'd). Cumulative freezing-degree-day records for CRREL for 1973-1982. The curves are based on the Hanover Cooperative Station's 30-year normal (1941-1970) and the CRREL meteorological station's 7-year average (1973-1980). Freeze-up dates are indicated by arrows.

Figure 10. Cumulative freezing-degree-day records from Post Pond.

**Table 4. Post Pond freezing-degree-day (0°C base) and ice thickness (cm) data.**

Winter	Freezing-degree-day totals			
	At freeze-up	At max. thickness	Between freeze-up and max. thickness	Max. ice thickness
1973-74	95	590	495	45
1974-75	105	610	505	47
1975-76	80	830	750	60
1976-77	40	920	880	—
1977-78	70	920	850	67
1978-79	110	790	680	58
1979-80	75	640	565	54
1980-81	22	721	699	59
1981-82	50	855	805	67

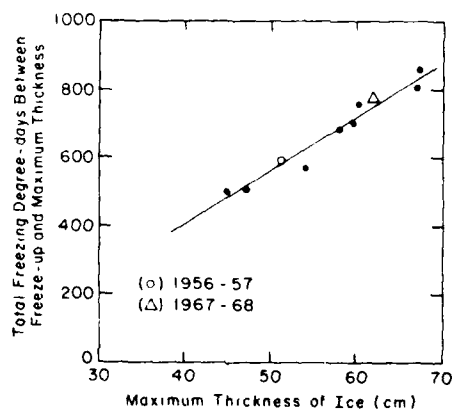
curve for the Hanover Cooperative Weather Station for 1941 to 1970 (U.S. Department of Commerce 1973). The CRREL and Post Pond records show that Post Pond was slightly colder during the 1974-75 winter; there were no significant differences between the sites in 1975-76. The normalized curves show that CRREL averages about 90 freezing degree-days colder than Hanover; this value agrees closely with the 80 degree-day difference in the 1973-74 winter (Gow and Langston 1977). The values are different because the CRREL weather station is more exposed than the Dartmouth (Hanover) observatory, where the winter temperature inversion associated with the elevated and sheltered position of this observatory moderates the air temperatures.

Freezing-degree-day (°C) records also demonstrate year-to-year variations in winter temperature regime and trends. For example, the temperatures for the 1973-74 winter at CRREL don't depart significantly from the 7-year average. The winter of 1974-75 was appreciably warmer than average. The next four winters were much colder than the 7-year normal; the freezing-degree-day indices at the end of those winters all exceed 800, and the index for the 1976-77 winter exceeds 950, a value close to the maximum expected for this location. The 1979-80 winter temperatures were higher than the 7-year normal until a cool period in late February raised the index to nearly normal. The end-of-winter indices for 1980-81 and 1981-82 were higher than normal.

Freeze-up dates can vary by as much as a month (from late November to late December), and the freezing-degree-day totals at freeze-up can also vary, depending on the weather during autumn and immediately preceding ice formation (Table 4). The two lowest totals of freezing degree-days

at freeze-up coincided with the earliest freeze-up dates recorded during the 1973-1982 period, 29 November 1976 and 6 December 1980. Both events were preceded by lower-than-normal fall temperatures, which would promote the early formation of a stable ice cover if followed by seasonable December air temperatures.

Freezing-degree-day totals at maximum ice thickness also varied greatly from year to year, ranging from 550 in 1974-75 to 920 in 1977-78 (Table 4). The measure most closely related to ice growth is the freezing-degree-day total accumulated between freeze-up and maximum thickness; Table 4 shows that the thinnest (45 cm) and thickest (67 cm) ice sheets correspond to the lowest and



**Figure 11. Seasonal ice-thickness maxima vs freezing-degree-day (°C) totals accumulated between freeze-up and ice maximum at Post Pond (including measurements for 1973 to 1982 and for the winters of 1956-57 [Ragle 1963] and 1967-68 [Parrott and Fleming 1970]).**

highest freezing-degree-day totals, respectively. The ice thickness and the number of freezing degree-days between freeze-up and maximum thickness are linearly related over the entire range of ice thicknesses measured on Post Pond (Fig. 11). Despite the two-part nature of the ice sheets that form on Post Pond, this relationship is not affected by the amount of snow ice.

Long-term meteorological records maintained at the Hanover Observatory show that it is unlikely that freezing-degree-day totals accumulated between freeze-up and maximum ice thickness on Post Pond would ever exceed 900 or fall below 400. These values and the data from Figure 10 show that the maximum ice thickness on Post Pond should neither exceed 72 cm nor be less than 40 cm.

### Ice-growth predictions

The simple empirical relationship for estimating ice thickness  $n(t)$  is

$$n(t) = \alpha \sqrt{\Sigma S_s} \quad (2)$$

where  $\Sigma S_s$  is the sum of the freezing degree-days between freeze-up and ice maximum and  $\alpha$  is a numerical coefficient. The value of  $\alpha$  may be estimated from

$$\alpha = \sqrt{2K_i / \rho_i \lambda} \quad (3)$$

where  $K_i$  is the thermal conductivity of ice,  $\rho_i$  is the ice density, and  $\lambda$  is the latent heat of fusion of ice. The value of  $\alpha$  for ice growth under conditions of perfect heat transfer is  $0.000121 \text{ m s}^{-1/2} \text{ } ^\circ\text{C}^{-1/2}$ . Because heat transfer conditions are normally less than ideal, an additional correction factor  $\beta$  has to be applied. Accordingly

$$\alpha = \beta(0.000121). \quad (4)$$

For snow-covered ice sheets on lakes  $\beta$  varies from 0.5 to 0.7 (Michel 1971). A value of 0.6 was chosen for Post Pond, giving a final correction coefficient  $\alpha$  of  $0.00007 \text{ m s}^{-1/2} \text{ } ^\circ\text{C}^{-1/2}$ .

Measured and computed ice-growth curves are presented in Appendix B. For most winters the measured and predicted values of ice thickness agree reasonably well. The greatest departures appear to be in those years with substantial snowfall. From trial computations with an ice-growth equation (Ashton 1978), which incorporates both the insulating effect of a snow cover and the heat-transfer effect of wind, it was determined that even a thin layer of snow or a relatively low wind

speed could dramatically influence the magnitude of ice growth. To demonstrate this effect for Post Pond, curves were recomputed to include the effect of a 6-cm-thick snow layer and a wind speed of 4.5 m/s. The choice of 6 cm to approximate the real conditions was based partly on observations of the snow cover on Post Pond, and partly on the record of snow depths measured each year at CRREL. The measured growth curve can be satisfactorily correlated with one of the two predicted ice-growth curves, depending on the winter's pattern of snowfall. These relationships are especially well illustrated in extreme years; for example, the actual curve and the predicted curve without a snow cover for the "snowless" winters of 1979-80 and 1980-81 show excellent agreement. For the winter of 1975-76, which had abundant snowfall, ice growth predicted on the basis of a 6-cm-thick snow cover correlates very closely with the measured ice-growth curve.

### SUMMARY AND CONCLUSIONS

Beginning with the winter of 1973-74 the growth and decay of ice covers on Post Pond, New Hampshire, have been monitored each year to 1981-82. This 9-year record of observations included ice thickness measurements, identification of the various ice types contributing to the ice cover, and measurements of meteorological parameters for correlating with and modeling ice growth. Freeze-up, leading to the establishment of a stable ice cover, occurred during the 4-week period from the end of November to the end of December. Maximum seasonal ice thickness was usually reached during the first two weeks of March, with times from freeze-up to maximum ice thickness ranging from 65 to 105 days. Maximum measured ice thicknesses ranged from 45 to 67 cm. The regional freezing-degree-day ( $^\circ\text{C}$ ) records indicate that ice thicknesses on Post Pond are not likely to exceed 72 cm or be less than 40 cm. Ice-out, corresponding with the date that Post Pond loses all its ice, usually occurred during the second and third weeks of April. The time from freeze-up to ice-out ranged from 116 to 141 days. Ice growth computed on the basis of freezing-degree-day records, including the effects of a snow cover, yielded results in reasonable agreement with observations.

Ice growth occurs predominantly by the direct freezing of lake water, but snow ice, formed by the freezing of water-soaked snow, can account for as much as 50% of the total ice thickness. The loss of ice from Post Pond is dominated initially

by melting from the top, which may result in as much as a halving of the ice thickness before bottom melting begins. Mechanical deterioration of the ice cover by candling is also a major factor in speeding the disappearance of ice from Post Pond.

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## APPENDIX A: ICE-GROWTH RECORDS

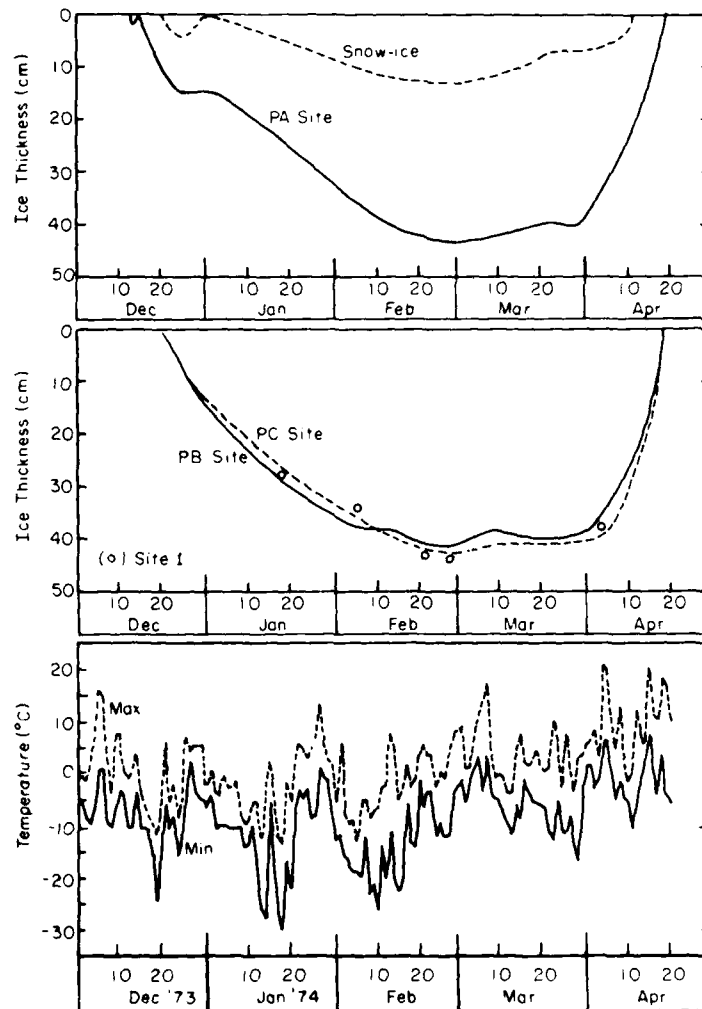


Figure A1. Ice growth on Post Pond and the daily maximum and minimum surface air temperatures at CRREL for the winter of 1973-74. (From Gow and Langston 1977.) (Thickness data from three other sites are included to demonstrate the small variability in ice thicknesses measured at various locations on Post Pond.) Initial freeze-over occurred during the night of 13-14 December. This produced a 4- to 5-cm-thick ice sheet, which melted completely during a warm period on 14 and 15 December. A steep decline in surface air temperatures followed, leading to freeze-up on 17 December. The ice cover attained its maximum thickness (45 cm) during the last week of February 1974. However, the ice sheet, composed of 13 cm of snow ice overlying 32 cm of lake ice, did not undergo any appreciable thinning until the second week of April. By 19 April the ice cover had disappeared completely.

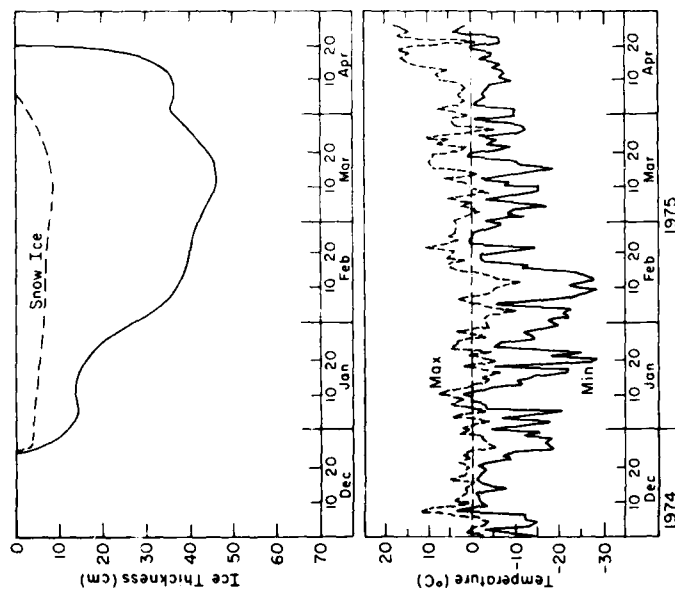


Figure A2. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at Post Pond for the winter of 1974-75. Skim ice began forming towards the end of November, but the lake did not completely freeze up until the evening of 25-26 December. Freeze-up was characterized by independent freezing on different parts of the lake until it became entirely ice-covered. Maximum ice thickness (47 cm) occurred during the second week of March. The ice cover, consisting of 9 cm of snow ice and 38 cm of lake ice, began thinning two or three days later and had melted completely within one month (20 April).

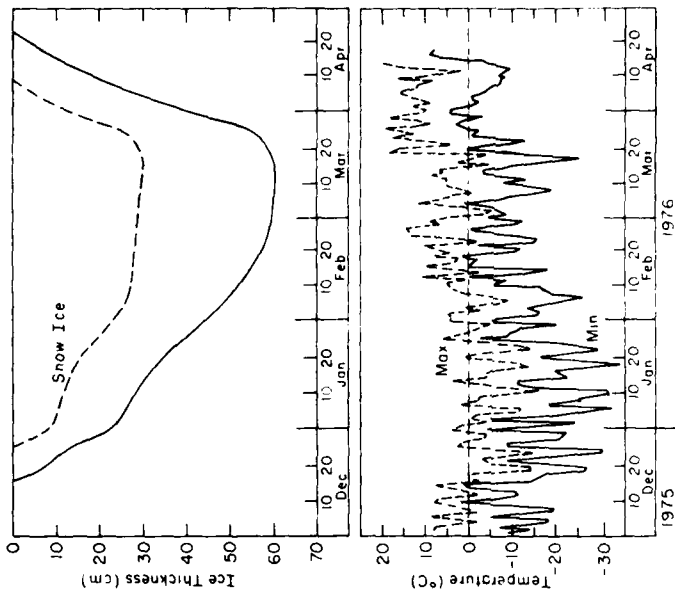


Figure A3. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at Post Pond for the winter of 1975-76. The lake froze over completely on 8 December but became ice-free by 12 December during a period of warm, rainy weather. Freeze-up occurred on the night of 16-17 December. A maximum ice thickness of 60 cm, including an unusually thick, 30-cm layer of snow-ice was measured on 16 March and was followed almost immediately by thinning of the ice cover by surface melting. All ice had disappeared by 20 April.



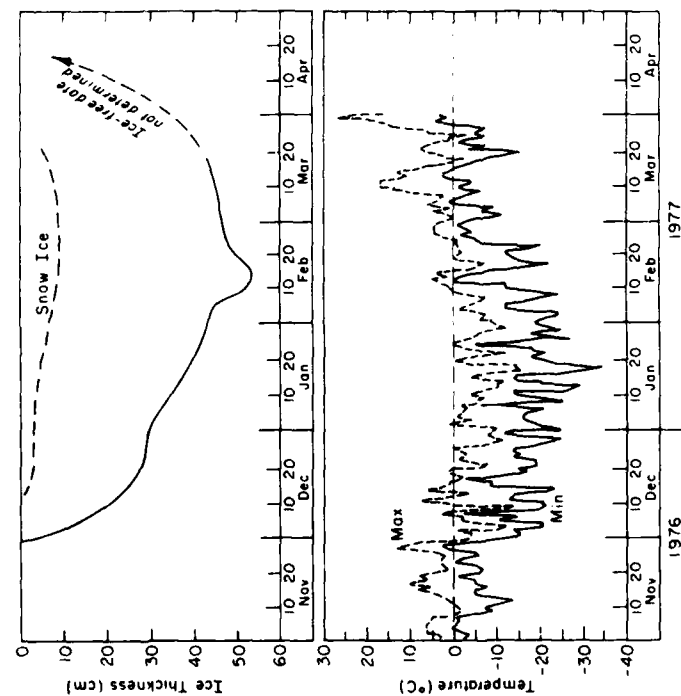


Figure A4. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1976-77. Sheet ice began growing on 23 November and continued forming until the surface of the lake became completely ice-covered by 29 November, the earliest freeze-up date recorded for the 9-year period of observations on Post Pond. Unfortunately, the activities of a large contingent of ice fishermen interfered with reliable measurements of ice thickness.

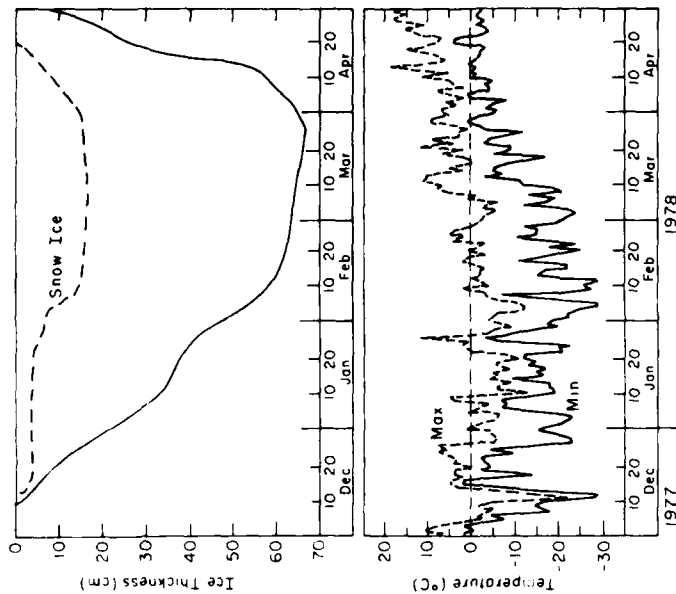


Figure A5. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1977-78. Ice began forming around the edges of the lake on 8 December and continued to grow towards the center of Post Pond until complete freeze-up occurred on 10 December. A maximum ice thickness of 67 cm, including 17 cm of snow ice, was recorded on 24 March 1978 and was followed by sustained melting, leading to complete dissipation by 29 April.

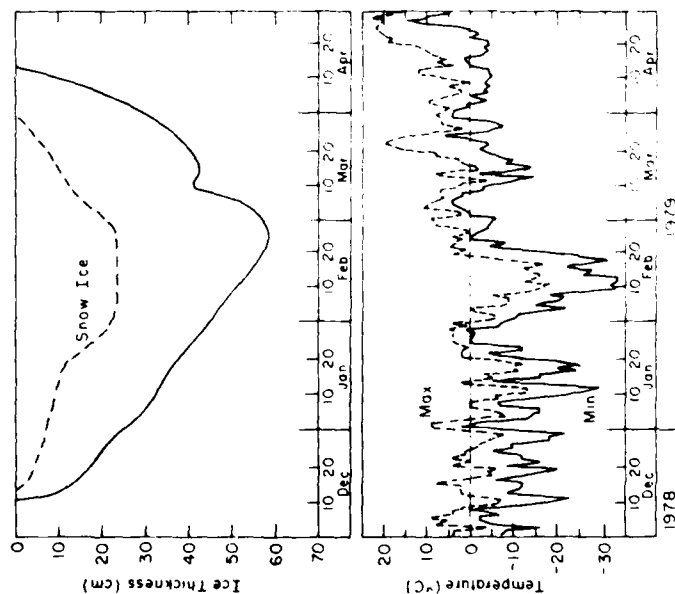


Figure A6. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1978-79. During the first week of December the ice grew outwards from the shore and attained a thickness of nearly 11 cm before the center of Post Pond finally froze over on 13 December. The ice cover continued to grow uniformly with time until 24 February, when it reached its maximum thickness for the season (58 cm, including 23 cm of snow ice). The lake became ice-free on 13 April.

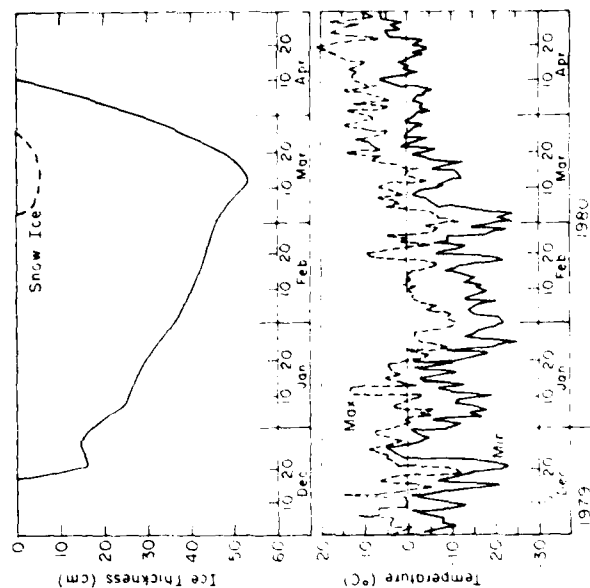


Figure A7. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1979-80. Post Pond had become 75% ice-covered by 17 December, 2-3 days after the first appearance of ice. Freeze-up was complete by 18 December. Ice grew rapidly over the next few days (15 cm of ice in less than 3 days). During the next 10 weeks the ice cover, composed almost entirely of frozen lake water, continued to grow at a very uniform rate of about 5 mm/day until it reached a maximum thickness of 54 cm, including just 5 cm of snow ice, on 12 March. This was followed almost immediately by melting of the ice at a rate of about 20 mm/day, about four times the freezing rate. By 13 April Post Pond had become completely ice-free.

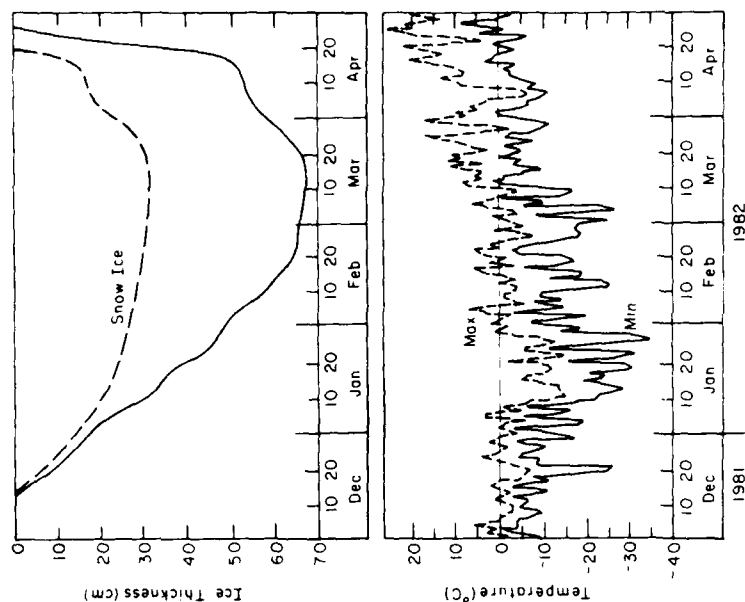


Figure A8. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1980-81. Freeze-up occurred on 6 December and was followed by exceptionally rapid ice growth, which averaged nearly 9 mm/day over the next 2 months. A maximum ice thickness of 59 cm, including just 4 cm of snow ice, was measured on 9 February. This was followed by unseasonably warm weather, resulting in the loss of nearly half the ice cover during the next 11 days. This in turn was followed by a renewal of ice growth that continued into the third week of March before the ice again began to melt. Ice-out occurred on 7 April.

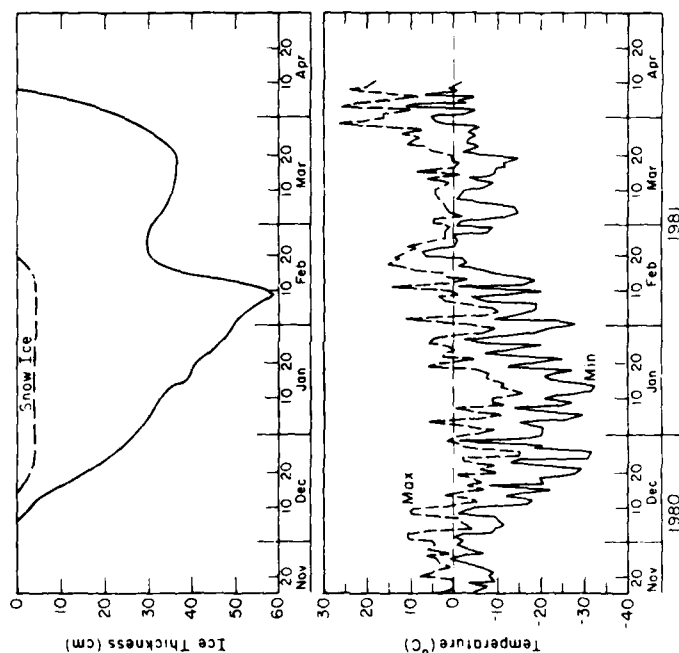


Figure A9. Ice growth on Post Pond and daily maximum and minimum surface air temperatures at CRREL for the winter of 1981-82. Freeze-up on 14 December coincided with sustained snowfall, leading to the formation of an ice sheet composed principally of snow ice in the top 20 cm. The ice sheet grew at a rate of about 9.5 mm/day until it reached a thickness of 65 cm by 20 February. A maximum ice thickness of 67 cm, including 31 cm of snow ice, was recorded on 15 March. The lake became ice-free on 27 April. Most of this loss was sustained during the two-week period beginning 14 April, when 52 cm of ice was melted, equivalent to a thinning rate of 37 mm/day.

## APPENDIX B: MEASURED AND COMPUTED ICE-GROWTH CURVES

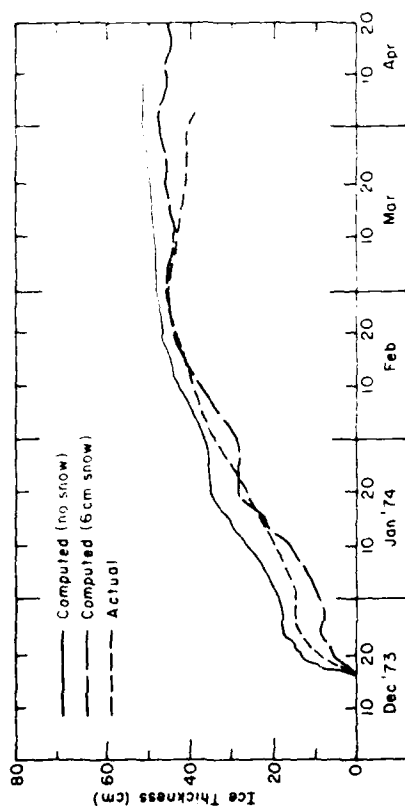


Figure B1. Measured and computed ice-growth curves for the winter of 1973-74 at Post Pond. The departure of the predicted ice growth from that actually measured is substantially decreased when the predicted curve incorporates the effect of a 6-cm snow cover. This result is in essential agreement with the snow distribution for this winter.

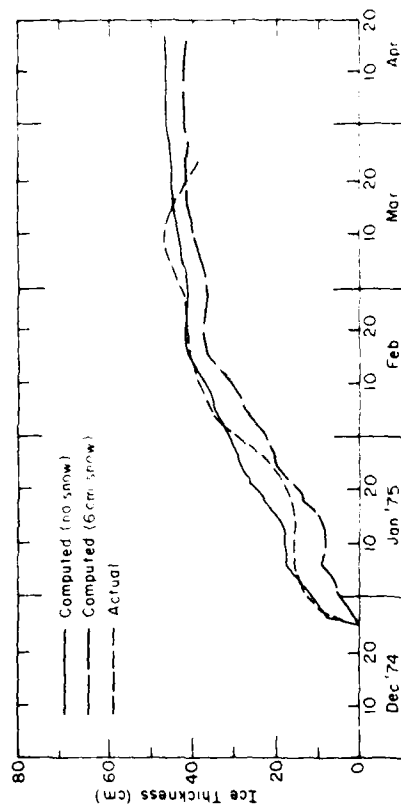


Figure B2. Measured and computed ice-growth curves for the winter of 1974-75 at Post Pond. This winter was characterized by less than normal snow fall, reflected by the small amount of snow ice and the generally snow-free ice cover. The good correspondence between actual ice growth and that predicted for snow-free ice supports these observations.

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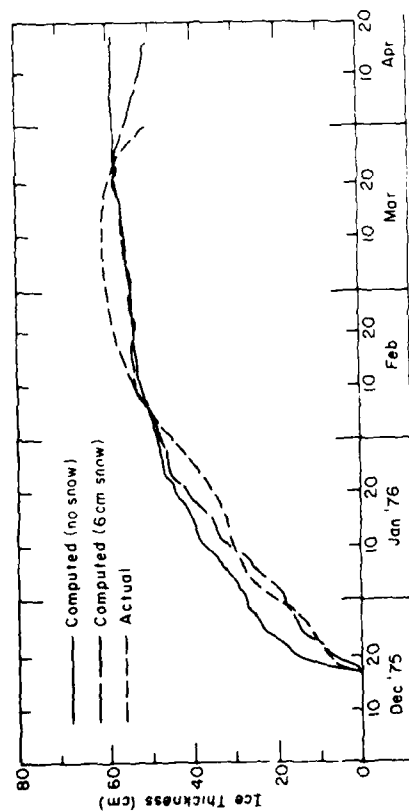


Figure B3. Measured and computed ice-growth curves for the winter of 1975-76 at Post Pond. This winter had substantial snowfall, resulting in extensive snow-ice (50% of the total ice thickness at the seasonal maximum). This agrees with ice growth predicted on the basis of a 6-cm snow cover, which provides a closer match with the measured growth than the predicted curve that neglects the effect of snow.

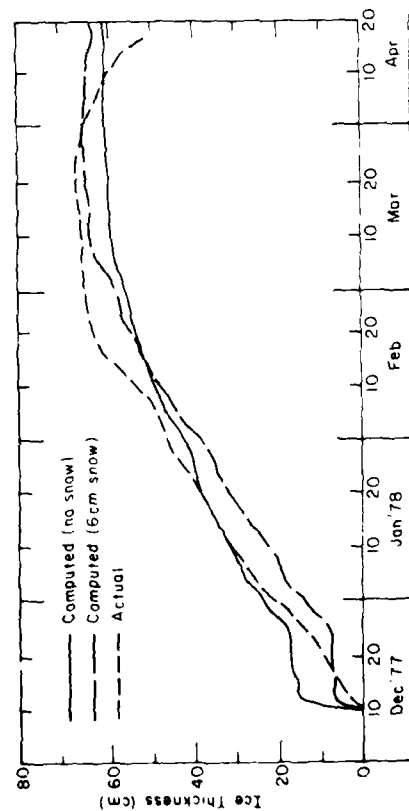


Figure B5. Measured and computed ice-growth curves for the winter of 1977-78 at Post Pond. A fair correlation exists between both computed ice-growth curves and that obtained from actual measurements. The growth predicted on the basis of a 6-cm-thick snow cover lags consistently behind the curve of actual growth, but both match closely in the region of maximum ice thickness.

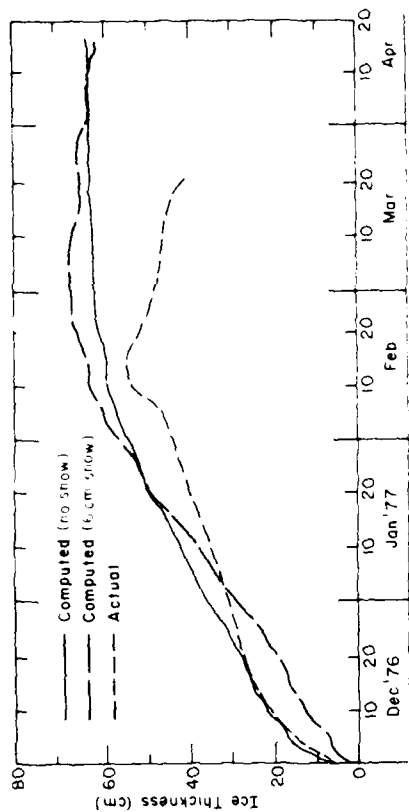


Figure B4. Measured and computed ice-growth curves for the winter of 1976-77 at Post Pond. Correlations between the computed and measured ice-growth curves were difficult because of the activities of ice fishermen during January and February. However, growth of the top 25 cm of ice, which formed before the fishermen arrived, conforms well with values predicted for the no-snow condition, a situation in accord with the lack of a snow cover during December 1976.

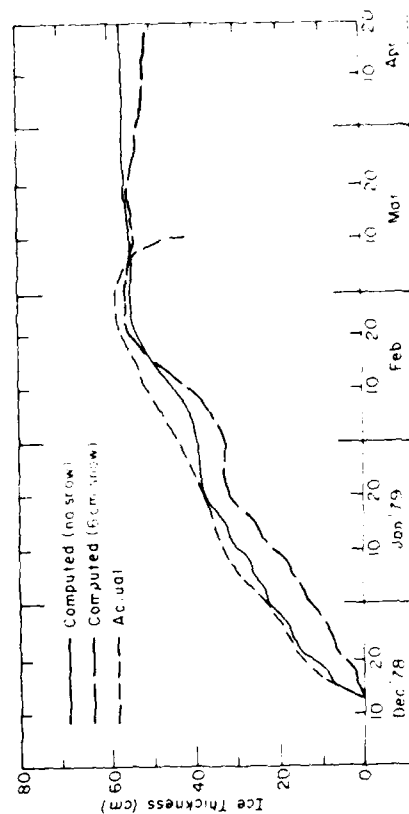


Figure B6. Measured and computed ice-growth curves for the winter of 1978-79 at Post Pond. The measured ice-growth curve agrees closely with growth predicted for an ice sheet lacking a snow cover. This result appears at odds with the formation of abundant snow-ice. A possible explanation, borne out by observation, is that the insulating effect of the snow was diminished significantly by its rapid conversion to snow-ice.

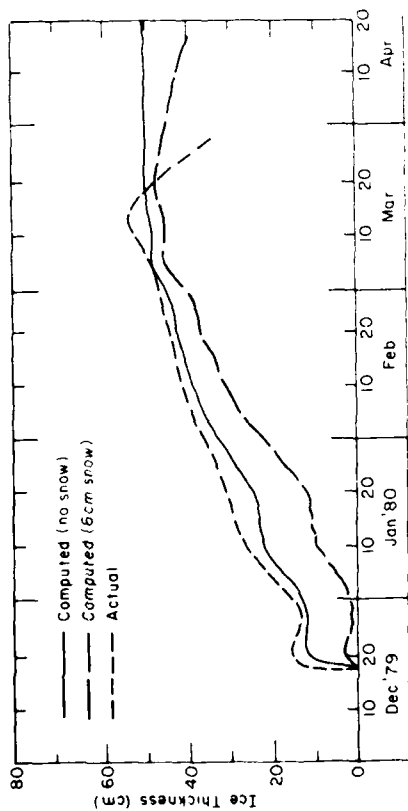


Figure B7. Measured and computed ice-growth curves for the winter of 1979-80 at Post Pond. This was the year of the "snowless" winter. Accordingly ice growth predicted on the basis of no snow cover agrees very closely with actual measurements of ice thickness.

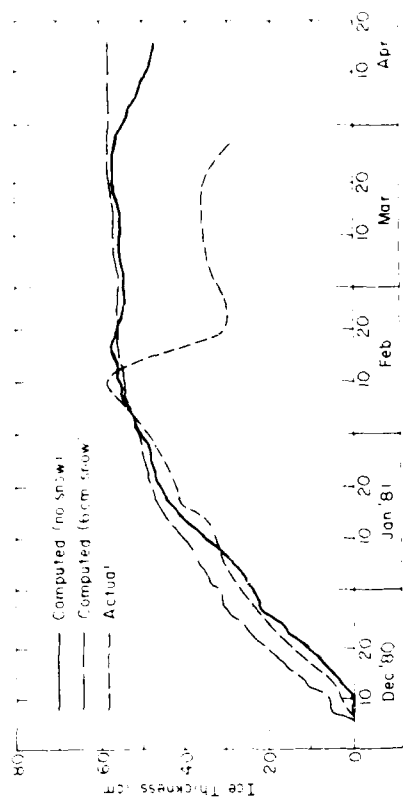


Figure B8. Measured and computed ice-growth curves for the winter of 1980-81 at Post Pond. The low snowfall of this winter is reflected in the good agreement between the measured ice growth and that predicted on the basis of no snow.

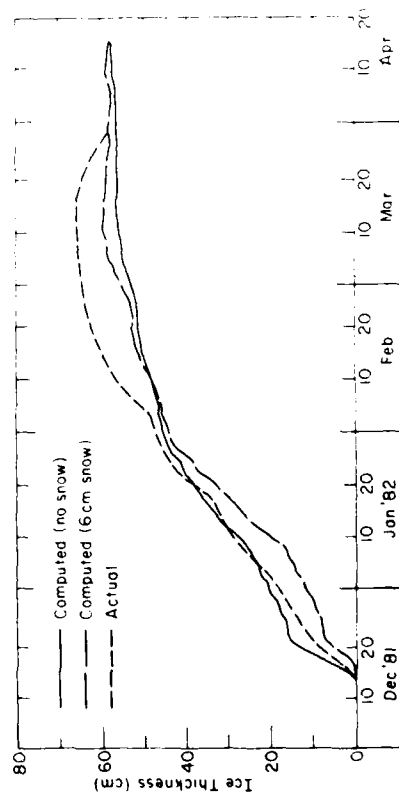


Figure B9. Measured and computed ice-growth curves for the winter of 1981-82 at Post Pond. This was a season in which substantial snowfall was recorded. Snow deposited concurrently with freeze-up led to an ice cover composed predominantly of snow ice in the top 20-25 cm. Interestingly the measured growth corresponds closer with that computed on the basis of the snow-free model than that incorporating a 6-cm snow cover. This result is probably because most of the snow was transformed to snow ice soon after it was deposited, significantly reducing its insulating effects.

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Gow, Anthony J.

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1. Ice growth. 2. Ice decay. 3. Ponds.

I. Govoni, John W. II. United States. Army. Corps of Engineers. III. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. IV. Series: CRREL Report 83-4.